Polarization- nhanc d Mg doping of AlGaN/GaN superlattic s

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The hole-transport properties of Mg-doped AlGaN/GaN superlattices are carefully examined. Variable-temperature Hall-effect measurements indicate that the use of such superlattices enhances the average hole concentration at a temperature of 120 K by over five orders of magnitude compared to a bulk GaN film (the enhancement at room temperature is a factor of 9). An unusual modulation-doping scheme, which has been realized using molecular-beam epitaxy, has yielded high-hole-mobility superlattices and conclusively demonstrated the pivotal role of piezoelectric and spontaneous polarization in determining the band structure of the superlattices. © *1999 American Institute of Physics.* [S0003-6951(99)04442-3]

The development of highly conductive p-type GaN and AlGaN is of crucial importance for a number of electronic and optoelectronic devices. The conductivity of Mg-doped GaN has been limited, however, by the deep nature of the Mg acceptor and consequent low acceptor ionization percentage, as well as the low hole mobility in heavily Mg-doped GaN.[1] The problem is even more severe in AlGaN alloys, where the doping efficiency at room temperature can be quite low.[2] The situation is further exacerbated when device operation at lower temperatures is desired, as these lower temperatures lead to a diminishing hole concentration.

The use of AlGaN/GaN heterojunctions has been proposed as a technique to increase the average hole concentration[3–5] and our recent work has provided an experimental demonstration of increased hole concentration at room temperature through the use of AlGaN/GaN superlattices.[6] The mechanism for hole enhancement is the periodic oscillation of the valence-band edge. Acceptors are ionized where the band edge is far below the Fermi energy and the resulting holes accumulate where the band edge is close to the Fermi level, forming a confined sheet of carriers. Although the free carriers are separated into parallel sheets, their spatially averaged density will be much higher than in a simple bulk film.

High electric fields due to both spontaneous and piezoelectric polarization within the strained AlGaN layers are expected to strongly impact the band bending within the superlattice.[7,8] In our earlier work we calculated the hole concentration expected from an AlGaN/GaN superlattice both with and without the polarization fields taken into account.[6] The fields create a periodic sawtooth variation in the band diagram as shown in Fig. 1. When the polarization fields are present, a strong dependence on the superlattice dimensions is obtained: thicker layers yield larger potential changes from the polarization fields, and therefore, higher

hole concentrations. In experimental measurements on Mg-doped $Al_{0.2}Ga_{0.8}N/GaN$ superlattices a similar dependence on layer thicknesses was observed, suggesting that the polarization fields dominated the hole enhancement. These samples were grown by metalorganic chemical vapor deposition (MOCVD) and Mg doping was applied uniformly throughout the superlattice (a severe memory effect[9] makes Mg modulation doping by MOCVD very difficult). The Mg-doped superlattices were approximately 0.4 μm thick, and were grown above several microns of unintentionally doped n-type GaN and an $In_{0.05}Ga_{0.95}N$ compliance layer to prevent cracking. The measured hole concentration (spatially averaged) and mobility for the Mg-doped $Al_{0.2}Ga_{0.8}N/GaN$ superlattices are shown in Fig. 2 as a function of L, the thickness of the GaN and AlGaN layers (the layer thicknesses were kept equal so that the superlattice period is $2L$).
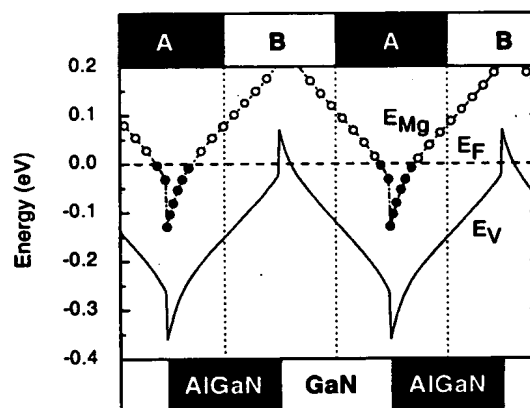

FIG. 1. Calculated valence-band diagram for the Mg-doped $Al_{0.2}Ga_{0.8}N/GaN$ superlattice with spontaneous and piezoelectric polarization fields taken into account. The thickness of each layer is $L = 80$ Å. The dashed line indicates the Fermi energy, and the circles represent the energy of the Mg acceptor (solid when ionized). Regions A and B defining each interface are indicated. The sapphire substrate is on the left and the free surface of the film is on the right.

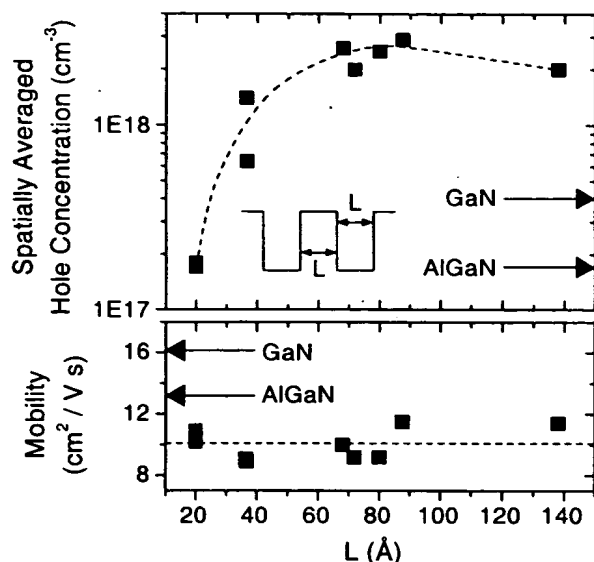[a] Electronic mail: kozodoy@indy.ece.ucsb.edu

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FIG. 2. Room-temperature Hall-effect measurements on uniformly Mg-doped MOCVD-grown $Al_{0.2}Ga_{0.8}N$/GaN superlattices. The superlattice dimension L is varied. The arrows indicate values obtained on bulk samples of Mg-doped GaN and $Al_{0.1}Ga_{0.9}N$. The dashed lines are eye guides.

TABLE I. Room-temperature Hall-effect measurements on modulation-doped $Al_{0.12}Ga_{0.88}N$/GaN superlattices.

Sample	Doped region	Hole Conc. (cm^{-3})	Mobility (cm^2/V s)
1	A	1.9×10^{18}	19
2	B	6.8×10^{17}	5.6

To determine the optimal modulation-doping scheme we examine the band diagram as shown in Fig. 1. In the absence of polarization fields the two types of AlGaN/GaN interfaces would be equivalent, but the polarization introduces charge sheets of opposite types at these interfaces. Assuming that the surface of the crystal is Ga face (this is the case when MOCVD is used to initiate growth on sapphire),[10] a positive sheet charge is obtained when AlGaN is grown on GaN. In this region, labeled region A, the bands are pulled down so that the acceptor ionization rate is high but the mobile hole concentration is low. Acceptor doping in this region is very effective since many of the acceptors will be ionized. At the opposite interface, region B, a negative sheet charge is obtained and the bands are pulled up—holes accumulate here, but the acceptor ionization rate is very low. Mg doping in this region will not yield many holes, but may considerably reduce the mobility of the accumulated carriers.

A high hole mobility is expected even in the case of uniform Mg doping because the polarization fields separate the mobile carriers from the ionized acceptors. The fairly low hole mobility values which were obtained in the uniformly doped films are attributed to interface scattering and poor material quality due to the high Mg concentration. The latter problem can be eliminated through modulation Mg doping limited to region A. We note that this modulation-doping scheme, where the dopant is applied across one interface, is very different from the traditional scheme used in nonpolar materials where the dopant is typically confined to the center of the barrier.

In order to achieve sharp dopant profiles, plasma-assisted molecular-beam epitaxy (MBE) was used to grow the modulation-doped superlattice samples. Secondary ion mass spectroscopy measurements have confirmed that very abrupt Mg profiles are obtained in these layers. The growths were performed on top of MOCVD-grown GaN base layers which were deposited on c-plane sapphire substrates. Two $Al_{0.12}Ga_{0.88}N$/GaN superlattice samples were prepared, both with $L = 80$ Å. In each case the Mg doping was applied

through only half the structure, either in region A or in region B. The two superlattice samples were prepared for room-temperature Hall-effect measurements using lithographically defined van der Pauw patterns; the results of the measurements are shown in Table I.

As expected, the sample doped only in region A exhibits both a higher hole concentration and a higher mobility value—the conductivity of this sample is almost an order of magnitude higher than that of the sample doped only in region B. This is an unambiguous demonstration of the crucial role played in these structures by polarization fields—without these fields the two interfaces are equivalent, and so, the two films should behave identically.

The sample doped only in region A also exhibits a higher mobility than the earlier, uniformly doped samples. This increase is attributed both to the improved material quality due to modulation doping and to reduced interface scattering due to a lower aluminum composition. Interface scattering has been shown to severely reduce the electron mobility in AlGaN/GaN heterojunction field-effect transistors,[11] and we expect the effect to be even stronger in p-type layers due to the very high hole mass.

Finally, we have investigated the low-temperature characteristics of these superlattices. Because the free carriers in these films result not from thermal ionization but from band-bending produced by the polarization fields, we expect that high p-type conductivity will be maintained even at low temperatures. Variable-temperature Hall-effect measurements, using magnetic fields between 1 and 2 T, have been performed on two samples: an AlGaN/GaN superlattice and a bulk Mg-doped GaN sample grown under similar conditions. Both films were grown by MOCVD. The superlattice sample is uniformly doped, contains 20% aluminum in the barriers, and has a dimension $L = 88$ Å.

The results of the Hall-effect measurements are shown in Fig. 3. At very high temperatures both samples exhibit the typical thermally activated hole concentration profile. As the temperature is reduced, the hole concentration in the bulk film continues to fall exponentially (below 120 K the measured hole concentration appears to increase again, indicating the onset of impurity conduction). The hole concentration in the superlattice film, however, remains fixed at approximately 2×10^{18} cm^{-3}, which is the spatially averaged hole concentration resulting from the polarization-induced bandbending. At room temperature the superlattice provides an enhancement of the hole concentration by approximately a factor of 9 compared to the bulk film. However, it is at lower temperatures that the superlattice provides the greatest advantage—the enhancement in hole concentration at a temperature of 120 K, for example, is over five orders of magnitude. It is also near this temperature that the mobility measured for carriers in the superlattice sample reached its peak:
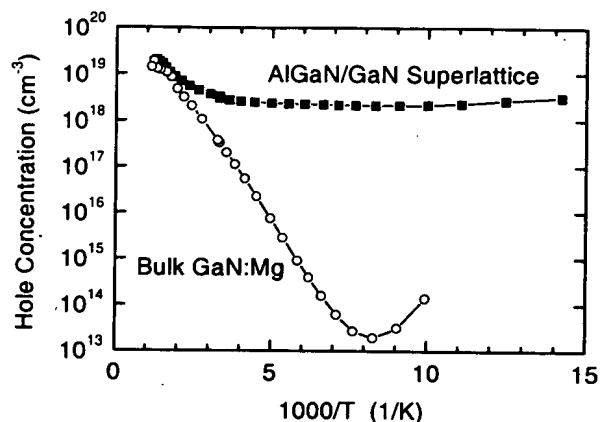
FIG. 3. Hole concentration as a function of temperature, as determined by variable-temperature Hall-effect measurements. The solid squares are values obtained from a uniformly doped, MOCVD-grown $Al_{0.2}Ga_{0.8}N/GaN$ superlattice with $L = 88$ Å; the open circles represent data from a bulk Mg-doped GaN film grown under similar conditions.

the highest value measured was $18\ cm^2/V$ s at a temperature of 140 K. The low-temperature mobility for the modulation-doped superlattice sample is expected to be considerably higher. It is clear from these measurements that the use of Mg-doped AlGaN/GaN superlattices will dramatically extend the usable temperature range for nitride-based devices requiring p-type conduction.

In conclusion, the hole-transport properties of Mg-doped AlGaN/GaN superlattices have been carefully examined.

Through the use of modulation doping at alternate interfaces, the critical role of polarization fields in the superlattice band structure has been conclusively demonstrated. The low-temperature performance of the uniformly doped superlattices has been measured and compared to that of bulk samples; the superlattice provides an enhancement in hole concentration of over five orders of magnitude at reduced temperatures.

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